2023

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary Set 2

Inside:

Free-Response Question 1

- ☑ Scoring Guidelines
- ☑ Student Samples
- ☑ Scoring Commentary

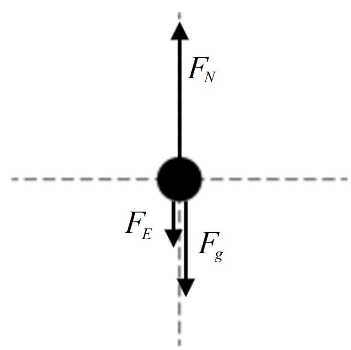
Question 1: Free-Response Question — 15 points

(a)	For correctly drawing and labeling the electrostatic force in the downward direction	**1 point**
	For drawing the normal force in the upward direction and a gravitational force in the downward direction	**1 point**

Scoring Note: F_S is an acceptable label to represent the force that the platform exerts on the sphere

Scoring Note: A maximum of 1 point may be earned if extraneous forces are included.

Example Response



Total for part (a) **2 points**

(b)	For applying an equation of the forces at equilibrium consistent with the diagram drawn in part (a)	**1 point**

Example Response

$$F_N - F_E - F_g = 0$$

For substituting a $k_s x$ or $k_s y$ that represents the normal force **1 point**

Example Response

$$k_s x - F_E - F_g = 0$$

For substituting a correct expression that represents the electrostatic force **1 point**

Example Response

$$F_E = \frac{1}{4\pi\varepsilon_0}\frac{qQ}{H^2}$$

For substituting a correct expression that represents the gravitational force **1 point**

Example Response

$$F_g = Mg$$

Example Solution

$$F_N - F_E - F_g = 0$$

$$F_N = F_E + F_g$$

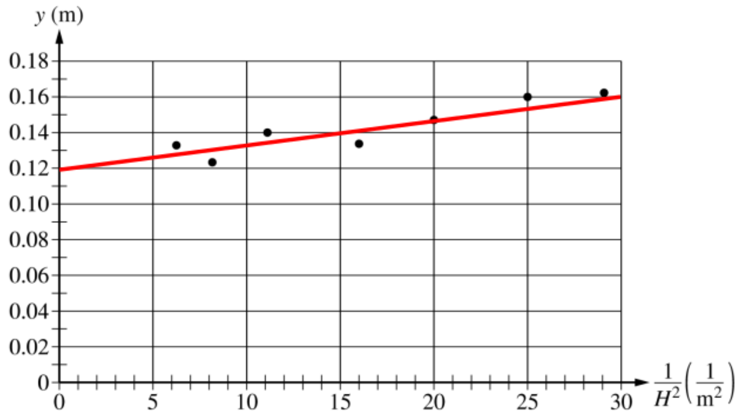
$$k_s y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{H^2} + Mg$$

$$y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$$

Total for part (b) **4 points**

(c)(i)	For a line that approximates the trend of the data	**1 point**

Example Response



(c)(ii) For using two points from the trend line drawn by the student to calculate the slope **1 point**

Scoring Note: Points of data may be used only if points of data are located directly on the line.

Example Response

$$\text{Slope} = \frac{\Delta y}{\Delta x}$$

$$\text{Slope} = \frac{\Delta(y)}{\Delta\left(\frac{1}{H^2}\right)}$$

$$\text{Slope} = \frac{(0.15\text{ m} - 0.12\text{ m})}{\left(20\ \frac{1}{\text{m}^2} - 0\ \frac{1}{\text{m}^2}\right)}$$

$$\text{Slope} = 0.0015\text{ m}^3$$

For indicating the relationship between the slope of the graph to ε_0 in the equation **1 point**

$$y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$$

Example Response

$$y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$$

$$\text{slope} = \left(\frac{Qq}{4\pi\varepsilon_0 k_s}\right)$$

For correctly substituting the value of the slope of the graph and other given quantities into the equation to calculate an experimental value of ε_0 **1 point**

Scoring Note: A numerical response without units may earn this point.

Example Solution

$$\text{slope} = \frac{Qq}{4\pi\varepsilon_0 k_s}$$

$$\varepsilon_0 = \frac{Qq}{4\pi k_s(\text{slope})}$$

$$\varepsilon_0 = \frac{\left(2\times10^{-6}\text{ C}\right)^2}{4\pi\left(25\frac{\text{N}}{\text{m}}\right)\left(0.0015\text{ m}^3\right)}$$

$$\varepsilon_0 = 8.5\times10^{-12}\ \frac{\text{C}^2}{\text{N}\bullet\text{m}^2}$$

(c)(iii)	For identifying that the y-intercept $= \frac{Mg}{k_s}$	**1 point**
	For correctly substituting the value of the y-intercept of the graph and other given quantities and constants into the equation to calculate an experimental value of M **Scoring Note:** A numerical response without units may earn this point.	**1 point**

Example Response

y-intercept = 0.12 m

$$y\text{-intercept} = \frac{Mg}{k_s}$$

$$M = \frac{(0.12\ \text{m})(25\ \text{N/m})}{9.8\ \text{m/s}^2}$$

$$M = 0.30\ \text{kg}$$

Total for part (c) 6 points

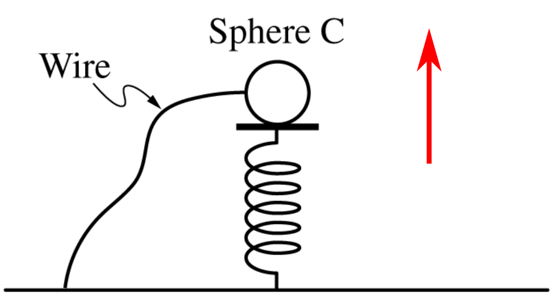
(d)(i)	For selecting "$y_2 < y_1$" with an attempt at a relevant justification	**1 point**
	For a justification that indicates correct charge rearrangement in Sphere C due to electrostatic force from Sphere A	**1 point**

Example Response

$y_2 < y_1$, *Charges are now free to move within Sphere* C *now that it is a conducting sphere. Electrons on Sphere* C *will be attracted to the excess positive charges on Sphere* A *and move closer to Sphere* A. *This leaves the opposite side of Sphere* C *more positively charged which results in less electric repulsion between the spheres and as a result less compression in the spring.*

(d)(ii)	For drawing an upward pointing arrow	**1 point**

Example Response



Total for part (d) 3 points

Total for question 1 15 points

Question 1

Begin your response to **QUESTION 1** on this page.

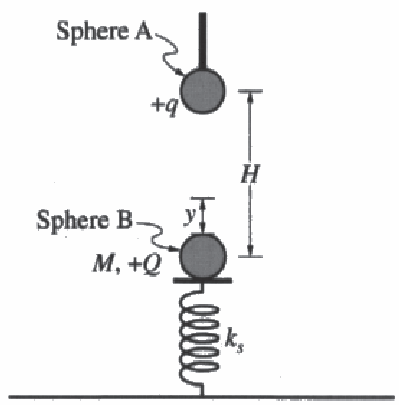
PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II

Time—45 minutes

3 Questions

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.



Note: Figure not drawn to scale.

1. Students perform an experiment to determine the value of vacuum permittivity ε_0. Sphere A is nonconducting with charge $+q$ and is attached to an insulating rod. Sphere B is nonconducting with charge $+Q$, and has mass M. Sphere B rests on an insulating platform of negligible mass that is attached to a vertical ideal spring with spring constant k_s. Sphere B and the spring are initially at rest.

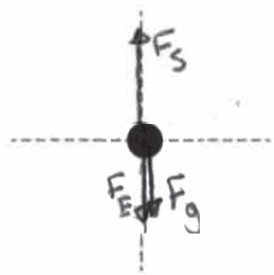
   Sphere A is then brought near Sphere B without touching. When the centers of the spheres are separated by a vertical distance H, the spring has been compressed a distance y, as shown in the figure. The students measure y for different values of H.

GO ON TO THE NEXT PAGE.

Question 1

Continue your response to **QUESTION 1** on this page.

(a) On the following dot that represents Sphere B in the figure on the previous page, draw and label the forces (not components) that are exerted on Sphere B. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



(b) Derive the relationship between y and H to show that $y = \frac{1}{4\pi\epsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$.

$F_{net} = 0$

$F_s - F_E - F_g = 0$

$F_s = F_E + F_g$

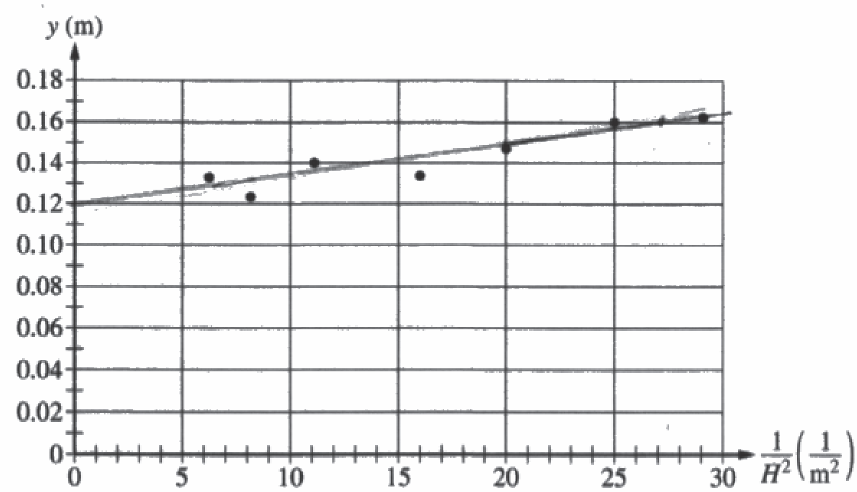
$k_s y = \frac{1}{4\pi\epsilon_0}\frac{Qq}{H^2} + Mg$

$y = \frac{1}{4\pi\epsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$

Question 1

Continue your response to **QUESTION 1** on this page.

(c) The students plot collected data of y as a function of $\frac{1}{H^2}$, as shown in the graph.



i. Draw the best-fit line for the data.

ii. Using the best-fit line, calculate an experimental value for the vacuum permittivity ε_0 when $Q = q = 2.00 \times 10^{-6}$ C and $k_s = 25$ N/m.

slope $= \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s}$ slope $= \frac{.16-.12}{27-0} = .00148$

$\Rightarrow .00148 = \frac{1}{4\pi\varepsilon_0}\frac{(2\times10^{-6})^2}{25}$

$\Rightarrow \varepsilon_0 = \frac{1}{4\pi \cdot .00148} \cdot \frac{(2\times10^{-6})^2}{25} = 8.59\times10^{-12}\ \frac{Nm^2}{C^2}$

iii. Using the best-fit line, calculate an experimental value for the mass of Sphere B.

y-intercept $= .12 = \frac{Mg}{k_s}$

$\Rightarrow .12 = \frac{M(10)}{25} \Rightarrow M = .3$ kg

Question 1

Continue your response to **QUESTION 1** on this page.

(d) The students modify the experiment by replacing nonconducting Sphere B with conducting Sphere C that has the same charge $+Q$ and mass M. Sphere A is brought near Sphere C without touching, compressing the spring. Sphere C comes to rest.

i. In the original experiment, when the centers of spheres A and B are a vertical distance H_1 apart, the spring is compressed a distance y_1. In the modified experiment, when the centers of spheres A and C are a vertical distance H_1 apart, the spring is compressed a distance y_2.

Is y_2 greater than, less than, or equal to y_1 ?

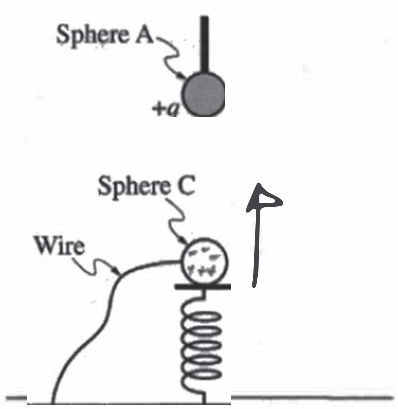
____ $y_2 > y_1$ ✓ $y_2 < y_1$ ____ $y_2 = y_1$

Justify your answer.

Since C is conducting, the charges can redistribute. Negative charges can move closer to Sphere A without Sphere being moved closer.
F_E is smaller overall so the spring has to provide less force itself

ii. Sphere C is then grounded with a wire. On the following figure, draw an arrow indicating the direction that the platform will move immediately after being grounded. If the platform remains stationary, write "does not move."

Q+



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PHYSICS C: ELECTRICITY AND MAGNETISM

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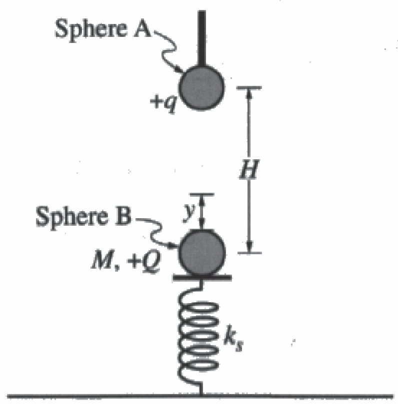

Note: Figure not drawn to scale.

1. Students perform an experiment to determine the value of vacuum permittivity ε_0. Sphere A is nonconducting with charge $+q$ and is attached to an insulating rod. Sphere B is nonconducting with charge $+Q$, and has mass M. Sphere B rests on an insulating platform of negligible mass that is attached to a vertical ideal spring with spring constant k_s. Sphere B and the spring are initially at rest.

   Sphere A is then brought near Sphere B without touching. When the centers of the spheres are separated by a vertical distance H, the spring has been compressed a distance y, as shown in the figure. The students measure y for different values of H.

GO ON TO THE NEXT PAGE.

Question 1

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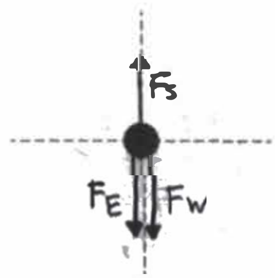

(b) Derive the relationship between y and H to show that $y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$.

$F_S = k|x|$ $\quad F_w = -mg$

$F_E = \frac{1}{4\pi\varepsilon_0}\frac{|q_1 q_2|}{r^2}$

$F_S = k_s y$ $\quad F_w = -Mg$ $\quad F_E = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{H^2}$

$\Sigma F = 0$

$k_s y - Mg - \frac{1}{4\pi\varepsilon_0}\frac{Qq}{H^2} = 0$

$k_s y = Mg + \frac{1}{4\pi\varepsilon_0}\frac{Qq}{H^2}$

$y = \frac{Mg}{k_s} + \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2}$

GO ON TO THE NEXT PAGE.

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Question 1

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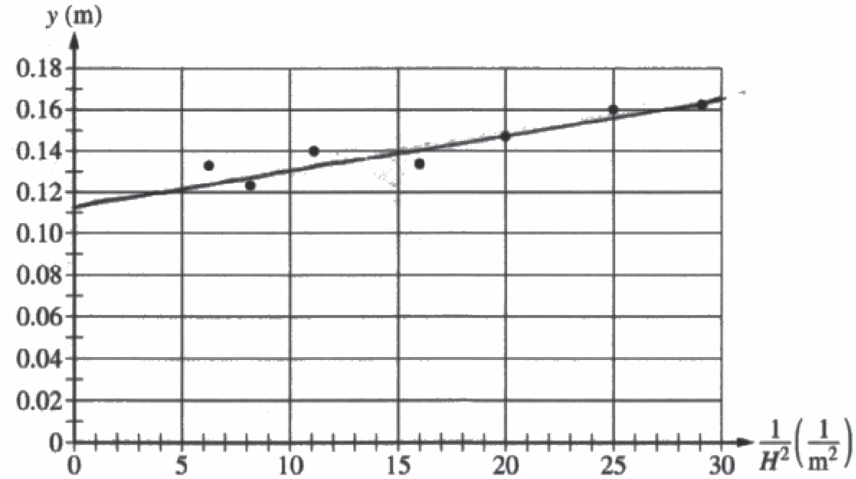

i. Draw the best-fit line for the data.

ii. Using the best-fit line, calculate an experimental value for the vacuum permittivity ε_0 when $Q = q = 2.00 \times 10^{-6}$ C and $k_s = 25$ N/m.

$$Y = \frac{Mg}{k_s} + \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2}$$

$$0.12 = \frac{Mg}{25} + \frac{1}{4\pi\varepsilon_0}\frac{(2\times10^{-6})(2\times10^{-6})}{25(0.2)^2}$$

$$0.12 = \frac{Mg}{25} + \frac{1}{4\pi\varepsilon_0}(8\times10^{-13})$$

iii. Using the best-fit line, calculate an experimental value for the mass of Sphere B.

$$Y = \frac{Mg}{k_s} + \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2}$$

  GO ON TO THE NEXT PAGE.

Question 1

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(d) The students modify the experiment by replacing nonconducting Sphere B with conducting Sphere C that has the same charge $+Q$ and mass M. Sphere A is brought near Sphere C without touching, compressing the spring. Sphere C comes to rest.

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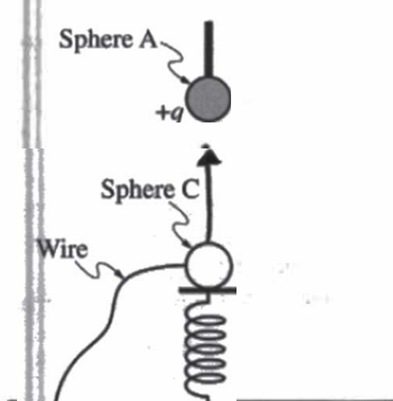
Is y_2 greater than, less than, or equal to y_1 ?

____ $y_2 > y_1$ ____ $y_2 < y_1$ __√__ $y_2 = y_1$

Justify your answer.

Whether it is a conducting or nonconducting sphere they both act as a point charge. Therefore nothing changes since it still has the same charge and mass.

ii. Sphere C is then grounded with a wire. On the following figure, draw an arrow indicating the direction that the platform will move immediately after being grounded. If the platform remains stationary, "does not move."



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PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II

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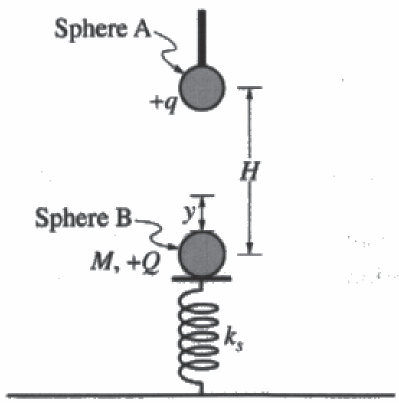

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Question 1

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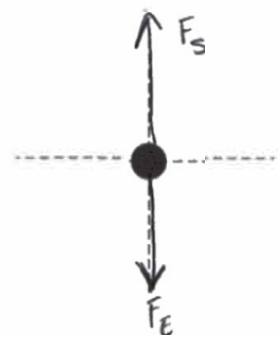

(b) Derive the relationship between y and H to show that $y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$.

$qV = \frac{kqq}{r}$

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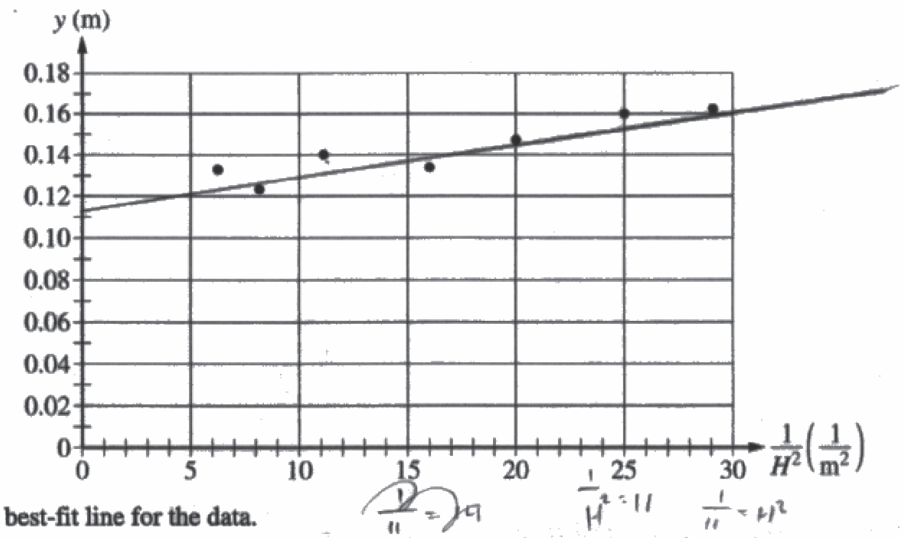
Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Q5601/8

Question 1

Continue your response to QUESTION 1 on this page.

(c) The students plot collected data of y as a function of $\frac{1}{H^2}$, as shown in the graph.



i. Draw the best-fit line for the data.

ii. Using the best-fit line, calculate an experimental value for the vacuum permittivity ε_0 when $Q = q = 2.00 \times 10^{-6}$ C and $k_s = 25$ N/m.

$y = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{k_s H^2} + \frac{Mg}{k_s}$

$.14 = \frac{1}{4\pi\varepsilon_0}\frac{(2E-6)^2}{25(.302)}$

$.14 = \frac{1}{4\pi\varepsilon_0} 5.298E-13$

$2.642E11 = \frac{1}{4\pi\varepsilon_0}$

$3.321E12 = \frac{1}{\varepsilon_0}$

$\boxed{3.011E-13 = \varepsilon_0}$

iii. Using the best-fit line, calculate an experimental value for the mass of Sphere B.

$.14 = \frac{1}{4\pi(3.011E-13)}\frac{(2E-6)^2}{25(.302)} + \frac{M9.8}{25}$

$.999 = \frac{M9.8}{25}$

$24.996 = M9.8$

$\boxed{M = 2.551 \text{ kg}}$

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Question 1

Continue your response to QUESTION 1 on this page.

(d) The students modify the experiment by replacing nonconducting Sphere B with conducting Sphere C that has the same charge $+Q$ and mass M. Sphere A is brought near Sphere C without touching, compressing the spring. Sphere C comes to rest.

i. In the original experiment, when the centers of spheres A and B are a vertical distance H_1 apart, the spring is compressed a distance y_1. In the modified experiment, when the centers of spheres A and C are a vertical distance H_1 apart, the spring is compressed a distance y_2.

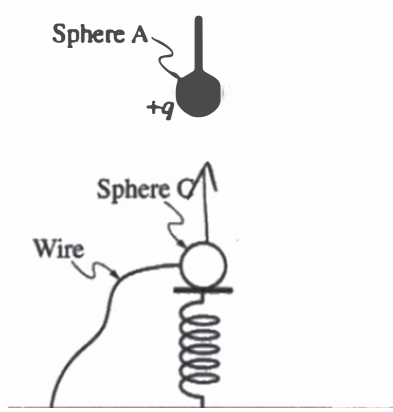
Is y_2 greater than, less than, or equal to y_1 ?

____ $y_2 > y_1$ ✓ $y_2 < y_1$ ____ $y_2 = y_1$

Justify your answer.

since sphere A is nonconducting and sphere C is, instead of repelling eachother so much, sphere C will induce sphere A, making the spring compress less

ii. Sphere C is then grounded with a wire. On the following figure, draw an arrow indicating the direction that the platform will move immediately after being grounded. If the platform remains stationary, write "does not move."



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Question 1

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

The responses were expected to demonstrate the ability to:

- Draw a free-body diagram indicating the forces exerted on a nonconducting, positively charged sphere resting on a spring-loaded platform near another positively charged sphere with correct directions and appropriate labels.
- Derive the relationship between the distance the spring will compress at equilibrium and the distance H between the two charged spheres to validate a given expression for distance d in terms of H.
- Draw a best-fit line that shows the trend of given data.
- Calculate the slope of the best-fit line and use the slope to find an experimental value of permittivity.
- Use the y-intercept of the best-fit line to calculate an experimental value for the mass of the sphere.
- Make a claim and provide justification for how charges move on a conducting sphere when near another charged sphere.
- Draw a representation of the motion of the grounded conducting sphere.

Sample: 1A
Score: 15

Part (a) earned 2 points. The first point was earned for including the electrostatic force from Sphere A on Sphere B labeled and in the correct direction. The second point was earned for including both the gravitational force and the spring force correctly labeled and in the correct directions. Part (b) earned 4 points. The first point was earned for indicating that the net force is zero. The second point was earned for correctly substituting an expression for the spring force using the given variables. The third point was earned for correctly substituting an expression for the electrostatic force using the given variables and constants. The fourth point was earned for correctly substituting an expression for the gravitational force using the given variables and constants. Part (c) earned 6 points. The first point was earned for drawing an appropriate trend line. The second point was earned for correctly calculating a slope value from the drawn trend line. The third point was earned for correctly relating the slope of the trend line to the equation so that a value for permittivity can be calculated. The fourth point was earned for correctly substituting the slope of the trend line and given values in an expression such that an experimental value of permittivity could be calculated. The fifth point was earned for correctly identifying the relationship between the y-intercept of the trend line and the mass of the sphere. The sixth point was earned for correctly substituting the y-intercept of the trend line along with given variables and constants into an expression such that an experimental value of the mass of the sphere could be calculated. Part (d) earned 3 points. The first point was earned for correctly indicating $y_2 < y_1$ and attempting a relevant justification. The second point was earned for providing a correct justification referring to the charge rearrangement of Sphere C. The third point was earned for indicating the correct upward direction.

Question 1 (continued)

Sample: 1B
Score: 8

Part (a) earned 2 points. The first point was earned for including the electrostatic force from Sphere A on Sphere B labeled and in the correct direction. The second point was earned for including both the gravitational force and the spring force correctly labeled and in the correct directions. Part (b) earned 4 points. The first point was earned for indicating that the net force is zero. The second point was earned for correctly substituting an expression for the spring force using the given variables. The third point was earned for correctly substituting an expression for the electrostatic force using the given variables and constants. The fourth point was earned for correctly substituting an expression for the gravitational force using the given variables and constants. Part (c) earned 1 point for drawing an appropriate trend line. The second point was not earned because the response does not correctly calculate a slope value from the drawn trend line. The third point was not earned because the response does not correctly relate the slope of the trend line to the equation so that a value for permittivity can be calculated. The fourth point was not earned because the response fails to substitute the slope of the trend line and given values in an expression such that an experimental value of permittivity could be calculated. The fifth point was not earned because the response fails to identify the relationship between the y-intercept of the trend line and the mass of the sphere. The sixth point was not earned because the response does not correctly substitute the y-intercept of the trend line along with given variables and constants into an expression such that an experimental value of the mass of the sphere could be calculated. Part (d) earned 1 point for indicating the correct upward direction. The second point was not earned because the response did not indicate the correct choice. The third point was not earned because the response fails to provide a correct justification referring to the charge rearrangement of Sphere C.

Sample: 1C
Score: 4

Part (a) earned 1 point for including the electrostatic force from Sphere A on Sphere B labeled and in the correct direction. The second point was not earned because the response does not have the gravitational force labeled and in the correct direction. Part (b) earned no points. The first point was not earned because the response does not indicate that the net force is zero. The second point was not earned because the response does not substitute an expression for the normal force using the given variables. The third point was not earned because the response does not substitute an expression for the electrostatic force using the given variables and fundamental constants. The fourth point was not earned because the response incorrectly substitutes an expression for the gravitational force using the given variables and fundamental constants. Part (c) earned 1 point for drawing an appropriate trend line. The second point was not earned because the response does not correctly calculate a slope value from the drawn trend line. The third point was not earned because the response does not correctly relate the slope of the trend line to the equation so that a value for permittivity can be calculated. The fourth point was not earned because the response fails to substitute the slope of the trend line and given values in an expression such that an experimental value of permittivity could be calculated. The fifth point was not earned because the response fails to identify the relationship between the y-intercept of the trend line and the mass of the sphere. The sixth point was not earned because the response does not correctly substitute the y-intercept of the trend line along with given variables and constants into an expression such that an experimental value of the mass of the sphere could be calculated. Part (d) earned 2 points. The first point was earned for correctly indicating $y_2 < y_1$ and attempting a relevant justification. The second point was not earned because the response does not provide a correct justification referring to the charge rearrangement of Sphere C. The third point was earned for indicating the correct upward direction.